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The formation of bipolar planetary nebulae

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Abstract. Using a radiation-hydrodynamics code I follow the formation of planetary nebulae around stars of different mass. Because a more massive central star evolves much faster than a lower mass one, it is to be expected that this will affect the formation of the PN. For the stars I use the evolutionary tracks for remnants with masses of 0.605 $M_\odot$ and 0.836 $M_\odot$, taken from Blöcker (1995). The AGB wind is assumed to be concentrated in a thin disk, which in models without evolving stars leads to the formation of a bipolar nebula. I find that in the case of the 0.836 $M_\odot$ remnant the nebula indeed acquires a bipolar shape, whereas for the 0.605 $M_\odot$ remnant the shape is more elliptical. The reason for this is the time it takes to ionize the AGB material; if this happens sufficiently slowly the density distribution in the AGB wind will be smoothed out, leading to more elliptical shapes. If it happens quickly, the original density distribution (in this case a thin disk) is hardly affected. This result suggests that lower mass central stars will less easily produce bipolar nebulae, which is supported by observations.

Key words: planetary nebulae: general – Stars: post-AGB – hydrodynamics – Stars: evolution

1. Introduction

The formation of a Planetary Nebula (PN) is critically determined by the star which lives and evolves in the middle of it. The star produces both the wind and the photons which determine the shape and appearance of the nebula. This is why the most advanced models for the formation of PNe are combinations of hydrodynamic and photoionization calculations and include the evolutionary track of the star (Marten & Schönberner 1991; Mellema 1994, henceforth M94; Mellema 1995, henceforth M95; Steffen et al. 1997).

Calculations of the evolution of stars after the Asymptotic Giant Branch (AGB) phase show that this strongly depends on their mass (see e.g. Vassiliadis & Wood 1994; Blöcker 1995), and one might expect that this will have an effect on the formation of the nebula. A typical post-AGB track in the HR-diagram consists of two parts (Paczyński 1971). Initially the star contracts, evolving to higher effective temperatures at a constant luminosity; then as the energy production stops, the luminosity starts decreasing and the effective temperature starts dropping. The star reaches its highest temperature (several times 10^5 K) at the transition from the contraction to the cooling phase.

In the contraction phase the more massive stars are more luminous and can reach higher effective temperatures than the lower mass ones. The most striking difference is however the evolutionary time scale. The lowest mass stars can take several 10 000 years to reach their highest temperature, whereas the highest mass ones do the same in less than a 100 years. This has several interesting effects, such as a low probability to find more massive central stars in the contraction phase.

Because the stellar radiation determines to a large extent the appearance of the nebula, one would also expect the shape of the nebula to depend on the evolutionary track of the central star. Here I report the first, preliminary, calculations of this effect. To study this I use a radiation-hydrodynamics code which follows the formation of cylindrically symmetric PNe. This code has been tested and used extensively to study the formation of aspherical PNe.

In Sect. 2 I give a short description of the numerical method and initial conditions. Section 3 contains a description of the results, which are further discussed in Sect. 4. The conclusions are summed up in Sect. 5.

2. Model and code

The formation of the PN is modelled using the Interacting Stellar Winds (ISW) model. It is assumed that during the AGB phase the star lost a large amount of material with a cylindrically symmetric density distribution. As the star

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heats up during the post-AGB phase a fast wind starts sweeping up this AGB material, shaping a PN out of it. The AGB material is supposed to be denser in the equatorial plane (because of the presence of a binary companion or perhaps some other effect, see e.g. Livio 1997). Models of this type have been successfully used to explain aspherical PNe (see e.g. Frank & Mellema 1994; Mellema & Frank 1995ab; M95).

The code used to produce the models is a combination of a 2D hydrodynamics code (an approximate Riemann solver, described in Mellema et al. 1989) and a photo-ionization/cooling calculation. Each time step the heating due to photo-ionization and cooling due to the most important permitted and forbidden lines, as well as free-free radiation, are calculated. At the same time the time-dependent ionization fractions are calculated. This method is described in more detail in Frank & Mellema (1994a).

The initial conditions are the same as described in Frank & Mellema (1994b), Mellema & Frank (1995) and M95. In these the asphericity of the AGB wind is characterised by two parameters: the density contrast (the ratio between the density at the equator and at the pole), called q and a shape parameter B (in some of the previous work called β). For the two simulations presented here I used the same initial conditions for the AGB wind, see Table 1. The parameter B has the low value of 0.5, meaning that the AGB material is highly concentrated towards the equator. In the pure ISW model without stellar evolution effects this leads to the formation of a bipolar PNe, see e.g. Frank & Mellema (1994b).

The central star's evolution is taken from the work of Blöcker (1995). I use the tracks for 0.605 and 0.836 $M_\odot$ remnants. From the star's luminosity and effective temperature I calculate the fast wind, using the prescription from Pauldrach et al. (1988) based on the radiation pressure on lines. This procedure is the same as in M94 and M95. The exact parameters for the star and the AGB mass loss are listed in Table 1.

Table 1. Parameters for runs A and B

Run	A	B
$\dot{M}_{\rm AGB}$ ($M_\odot$ yr^{-1})	$1\,10^{-5}$	$1\,10^{-5}$
q	5	5
B	0.5	0.5
v_0 (m s^{-1})	$1.5\,10^4$	$1.5\,10^4$
T_0 (K)	$2.0\,10^2$	$2.0\,10^2$
stellar track ($M_\odot$)	0.605	0.836
r_0 (m)	$1\,10^{14}$	$1\,10^{14}$
Δr (m)	$1.5\,10^{13}$	$1.5\,10^{13}$
grid dimension	100×100	100×100

3. Results

Here I present the results of the two simulations. Figures 1 and 2 show some synthesized narrow-band images from these two simulations. These images were constructed by taking the two-dimensional output of the code and rotating it around the symmetry axis before projecting it on the sky. The angle at which all images are shown is 10°.

As was described in M95, the evolution in these types of models is quite complex because of the time dependence of both the stellar spectrum and the fast wind. The snapshots in the figures do not really do justice to the amount of information produced by the simulations. Nevertheless some trends can be discerned.

Run A displays the double shell evolution described in M95. Initially a shell is swept up by the H ionization front. It is this structure (called the I-shell in M95) which shows up most prominently in the Hα image. At the same time the fast wind is shaping a shell (called the W-shell in M95) inside of this, and it is this shell which shows up in the [O III] image. Figure 1 shows the situation at 1743 years after the end of the AGB when the star has reached an effective temperature of 28 000 K. The shape of both the I- and W-shell is more or less elliptical. As time goes by the W-shell will become the brighter one in all lines, but here I only followed the evolution until the time the nebula reached the edge of the computational grid.

Run B displays a very different behaviour. Here the ionization front does *not* produce a shell and the wind shapes a bipolar (butterfly) type of shell. This shell is most clearly seen in the Hα image. Because of the very high effective temperature of the star the [O III] image shows more of the surrounding material. But the morphology of both images is much more bipolar than the ones from run A. At a time of 507 years after the end of the AGB, the stellar effective temperature is 226 000 K.

4. Discussion

Both models are still in their early evolutionary stages and one should therefore be careful drawing far reaching conclusions, but it is clear that model A is on its way to become an elliptical double shell PN, whereas model B is tending to a more bipolar shape.

The physical reason behind this is the different time scales on which the central stars evolve. For the most massive star the increase in the number of UV photons is so fast that the ionization front never stalls to become a D-type front. In other words: the ionization is almost instant. This means that the original equatorially condensed density structure is not altered appreciably by the ionization process. In the 0.605 $M_\odot$ case, however, the ionization front progresses slowly as a D-type front, having a shock front running ahead of it. It is this D-front which produces the double shell structure. This is likely to be the expla-

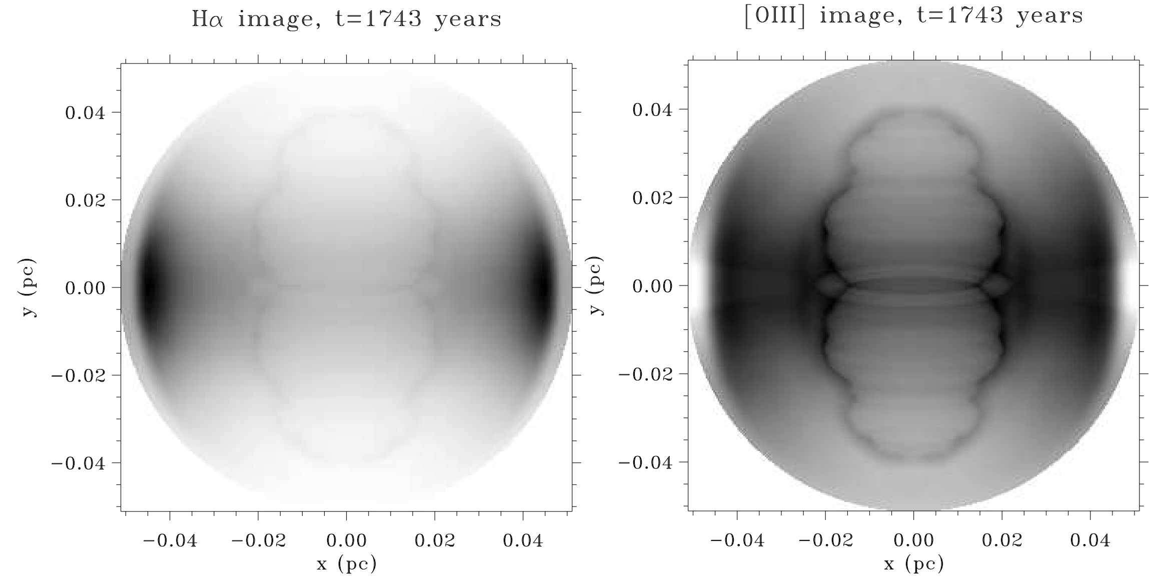

Fig. 1. Images in Hα (left) and [O III] (right) for run A

nation for the ‘attached haloes’ (Pasquali & Stanghellini 1995), as was already shown in M94.

M95 showed that the D-front can modify both the radial and tangential density distributions as it moves out. In the case shown in M95, the asphericity profile was smeared out somewhat, but this did not lead to a clearly different morphology because the initial density distribution was not very confined ($B = 1$). For the lower value of 0.5 used here, the change after the passage of the front is non-negligible. In run A the ‘effective B’ after the passage of the ionization front has been raised to about 1, leading to the formation of an elliptical nebula, whereas one would have expected a bipolar shape if there had been no modification by the ionization front. The surprise here is not that the high mass star forms a bipolar nebula, but rather that the low mass star does not!

This effect does not rule out the formation of bipolar PNe around lower mass stars, but it does make it harder for them to form and thus introduces a bias of bipolar shapes towards the more massive precursors. There is good observational evidence that bipolarity correlates quite well with stellar mass. Corradi & Schwarz (1995) studied a large sample of PNe and compared the properties of bipolars with those of elliptical PNe. Their conclusion was that the bipolar PNe form a separate group. They have on average a lower scale height in the galaxy, higher N abundance, and their central stars have higher effective temperatures. From this they conclude that on average the central stars must have higher masses. These conclusions were confirmed by Górny et al. (1997). Soker & Livio (1994) suggested an explanation in the frame work of a common envelope binary, and the results in this paper provide another one which can also be used to explain why not all known close binaries have bipolar PNe around them (Bond & Livio 1990). Stanghellini et al. (1993) did report a flat distribution of central masses for bipolar nebulae, but this was based on a smaller sample than the ones listed above.

The evolution described above is of course not the only possible one. In general one would expect a more massive star to have had a higher mass loss rate during the AGB, and thus a higher slow wind density. This effect is enforced by the fact that during the contraction phase the AGB material will be closer to the star, and hence less diluted. This material will thus be less easily ionized. But a more massive star is also more luminous and produces more ionizing photons, so these two effects may cancel. The observational evidence suggests that the densest parts of the AGB wind do remain largely neutral since bipolar nebulae often show molecular tori and effects of dust obscuration near the ‘waist’.

However, whether the AGB wind around these massive stars gets ionized or not is not essential for the formation of the bipolar nebula. The reason for this is that the initial evolution is fast. If an ionization front forms it will quickly reach its largest size and then as the star cools down, retreat again, or at best follow the wind-swept shell. The density distribution in the AGB wind will not be affected much by this and it is this which determines the final shape of the nebula.

The results in this paper do not mean that more massive stars will necessarily have bipolar nebulae around them. Whether or not this happens still depends on the mass loss geometry of the AGB wind and hence on the mechanism which produces the aspherical mass loss. If the mass loss is not strongly concentrated towards the equator, a bipolar PN will not form.

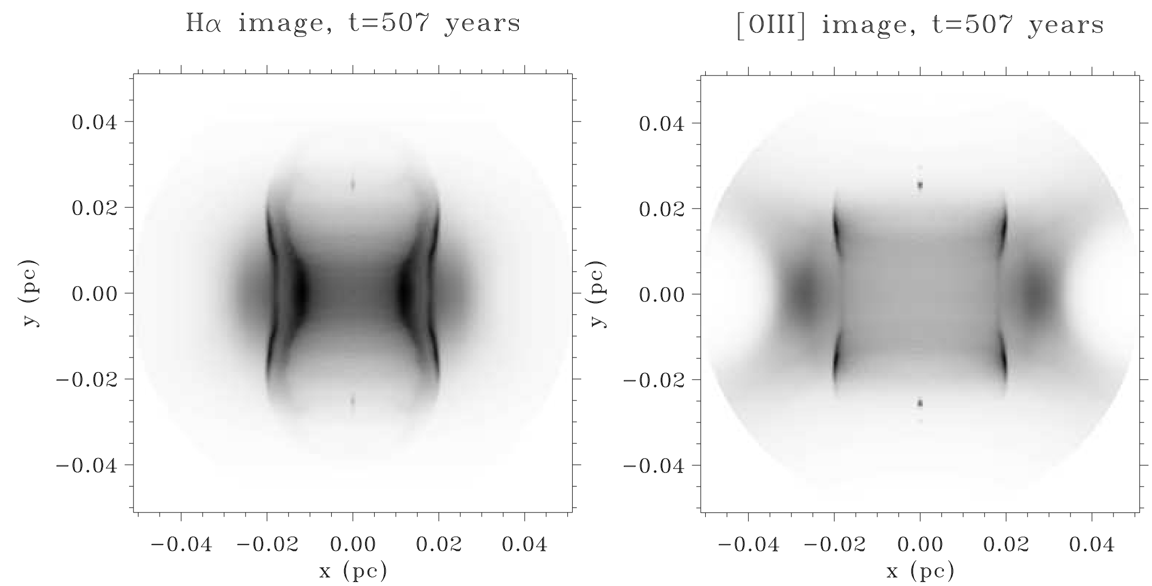

Fig. 2. Images in Hα (left) and [O III] (right) for run B

Note that the fact that symbiotic systems often also have bipolar nebulae around them does not support or contradict the explanation outlined above since it is difficult to say whether ionization is rapid or gradual in these systems.

5. Relation between AGB mass loss and PN shape

One conclusion from the ISW model is that the AGB wind density distribution determines the shape of the PN. This principle was used recently by Soker (1997) to derive a classification of PNe according to the processes which caused their progenitors to have an axi-symmetric AGB mass loss. Although there are a lot of assumptions that go into a classification like this, it is still useful to have it, if alone to focus further research. But the results in this paper show that one should be careful with trying to derive mass loss properties from PN morphologies. It shows that the same AGB mass loss geometry can result in very different morphologies for the PN. Depending on the mass of the central star the PN acquires either a bipolar shape or an elliptical with attached halo morphology. Other numerical studies of PN formation around evolving low mass stars also show the formation of attached haloes (Marten et al. 1994; M94; M95; Steffen et al. 1997). So, it appears that especially the presence of these attached haloes is an indication of a modification of the original density distribution. The observational result that almost all PNe with attached haloes are elliptical is fully consistent with this (Stanghellini & Pasquali 1995).

6. Conclusions

1. Numerical hydrodynamic models support the connection between massive stars and PNe with a bipolar morphology. The models show that it is more difficult for lower mass stars to acquire a PN with bipolar morphology, even if the initial conditions are favourable.
2. The reason for this is that for lower mass stars the ionization front is more likely to modify the surrounding density distribution, making it less equatorially concentrated. To produce bipolar nebulae one needs a density distribution with a high degree of concentration towards the equator.
3. Around more massive stars the original density structure is more likely to remain intact because either the material is so dense that it remains neutral and the ionization front lies within the wind swept shell, or the ionization is almost instantaneous (because of the rapid evolution) and does not modify the density structure.
4. Since an equatorially concentrated, disk-like density distribution is required for the formation of bipolar shapes, any mechanism giving rise to aspherical mass loss on the AGB should be able to produce this type of density distribution.

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